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Photosensitization in Relation to Mean and Standard Deviation Values

By

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Fordham University

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PHOTOSENSITIZATION IN RELATION TO MEAN AND STANDARD DEVIATION VALUES[1]

RICHARD T. ZEGERS

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THE RESEARCH described in this report covers a period of four years and was carried out as the result of a contract between the Office of Naval Research and Fordham University. This contract had its inception in a conversation between W. J. Crozier of Harvard University, William Berry of the Office of Naval Research, and the author. Crozier, making inferences from his own data, held that the human eye underwent a process of photosensitization when it operated at low levels of illumination. He believed that the evidence warranted an investigation to determine whether or not the process existed. The author agreed with him and undertook the work in 1952. The experimental design, to be described in Part 2, was explained to Crozier who felt it capable of revealing the process if it existed.

This process is defined as follows: If a monochromatic test signal light is flashed against a zero background and then against a series of monochromatic backgrounds, each of which is of a slightly higher intensity than the preceding, the energy in the flash of light, required for an *S* to see the flash 50% of the time, will decrease from that required at zero background, pass through a minimum at low levels of background intensity, and then rise according to the generally accepted principle of increase of $\triangle I$ with an increase of background intensity.

In order to test this hypothesis, four wavelengths of monochromatic light were selected. Each wavelength, when used as a signal light, was tested against itself and against the other three as backgrounds. In the choice of stimulus wavelengths, it was decided to use one from each of the main sections of the spectrum. A blue of 480 mμ, a green of 509 mμ, a yellow-green of 550 mμ, and a red of 670 mμ were chosen. By using each one of these wavelengths, as a signal, against each as a background, the different color systems would be given an opportunity to reveal whether or not they functioned according to the demands of the hypothesis. After extensive testing of two

[1] The data of this report were gathered and processed under contract between the Office of Naval Research and Fordham University, contract Number N-onr-880-(00)-(01), covering the period from June 30, 1952 to July 1, 1956. The work was carried out by the Visual Laboratory of the Psychology Department under the direction of the author.

The author wishes to express his gratitude to the many people who assisted him in this research, especially to Donald J. Dillon, Amadeo P. Georgi, John A. Malone, George F. Nolan, Joseph E. Sturr, and Mrs. Rudolph L. Zlody who acted either as *Ss* or as experimenters when the author, himself, was *S*.

Half of the data reported in Part 4 will constitute the experimental basis of the Ph.D. thesis of Mrs. Zlody. The data of Part 5 formed the basis for the M.A. theses of C. Claude Brodeur, Aime Hamann, William J. O'Halloran, and Jaime Bulatao. These theses were carried out under the mentorship of the author and were integrated by him into the research program of the visual laboratory.

My sincere appreciation is extended to E. Horace Siegler, Abraham Savisky, and Vincent Coates of the Perkin-Elmer Corporation for many technical and theoretical insights given during the construction of the colorimeter; to Philip Nolan and Bennett Sherman of the Farrand Optical Company for their assistance in developing the calibrating procedures; to Anne Anastasi for her discerning judgment in things statistical; to Forrest L. Dimmick for his helpful advice; and last but far from least to my former professor and mentor, Clarence C. Graham, who is always ready with the inspirational answers to a researcher's problems.

*S*s with these four wavelengths, the results were negative.

In order to explain these negative findings, the hypothesis was formulated that photosensitization is a phenomenon which manifests itself only as the result of the interaction of combinations of definite pairs of wavelengths. Once this hypothesis was suggested, a second hypothesis immediately presented itself. If photosensitization is a process which depends upon the interaction of specific signals with specific backgrounds, then the combinations of signal and background, which yield the phenomenon, depend upon the visual characteristics of the individual *S*. This secondary hypothesis was checked first. Crozier had offered evidence to show that the standard deviation of the logarithm of threshold energy varied periodically as a function of wavelength. It was decided to verify this pattern of variability and to use it as a guide for future experimentation. If individual *S*s, when tested, display the same periodic function with the maxima and minima located at exactly the same wavelengths, then it would be expected that photosensitization does not depend upon the peculiar characteristics of the *S*. Contrariwise, if it could be demonstrated that the maxima and minima of this periodic variability were definitely a function of the individual, then the negative results of the first part of the experiment might be explained in terms of the wavelengths which had been selected.

To investigate this latter hypothesis, a second experiment was devised. In this, two *S*s obtained frequency of seeing curves yielding means and standard deviations at 10 mμ intervals throughout the visual spectrum. An analysis of these data led to the tentative conclusion that maxima and minima of the standard deviations were functions of the individual involved. This necessitated a full-scale investigation of the problem of the periodic variability of the standard deviation. Moreover, it demanded investigation in a way that would give an index of the reliability of the data and show the scope of the phenomenon with reference to several psychophysical methods. The investigators agreed that if the standard deviation was really a measure of something over and above individual variability, and this to an important degree, evidences of such variability should be obtained regardless of the method used to gather the data.

When the data from this experiment failed to yield decisive results, specific investigation of the variability of an *S*'s standard deviation from session to session was undertaken. For this purpose, eight wavelengths, in two groups of four, were selected. Two groups of two *S*s each were tested on four of the eight wavelengths. This investigation consisted in obtaining 10 frequency-of-seeing curves per *S* per wavelength in an attempt to obtain a fair sample of day-to-day variability. Again the results were negative.

The final phase of the investigation consisted in studying the interaction of wavelength and field size on the pattern of the standard deviation. The mean values obtained from the frequency-of-seeing curves of this last phase were, because of calibration procedures, given in terms of radiometric units, i.e., microwatts. Calculations based on these data permitted presentation of the results in terms of a quanta-per-cone ratio.

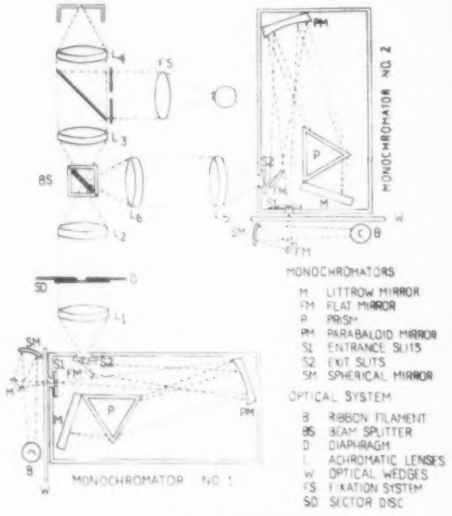

FIG. 1. Early model of the colorimeter.

Apparatus

The apparatus grew in the course of the experiment. Parts 1 and 2 were carried out when the colorimeter had only two monochromators. By the time Parts 3–6 were begun, two more monochromators had been added. With the initiation of Part 7, a thermocouple, amplifier, Ballantine voltmeter, powerpack, and auxiliary equipment had been acquired, making it possible to estimate the number of quanta involved in the threshold measurements. Schematic diagrams of the earlier and present apparatus are presented in Fig. 1 and 2, respectively. Basically, the earlier system would be the same as the present one when only Monochromators *2* and *4* are used. A detailed description of the present apparatus will be simplified if the monochromators, the optical system, and finally the auxiliary equipment required for its operation are considered separately.

Monochromators

The four monochromators are Perkin-Elmer Universal Monochromators, Model 83. These are Littrow-type prism monochromators. In this research, each monochromator was equipped with a 6-v., 9-amp. tungsten vertical ribbon filament bulb,

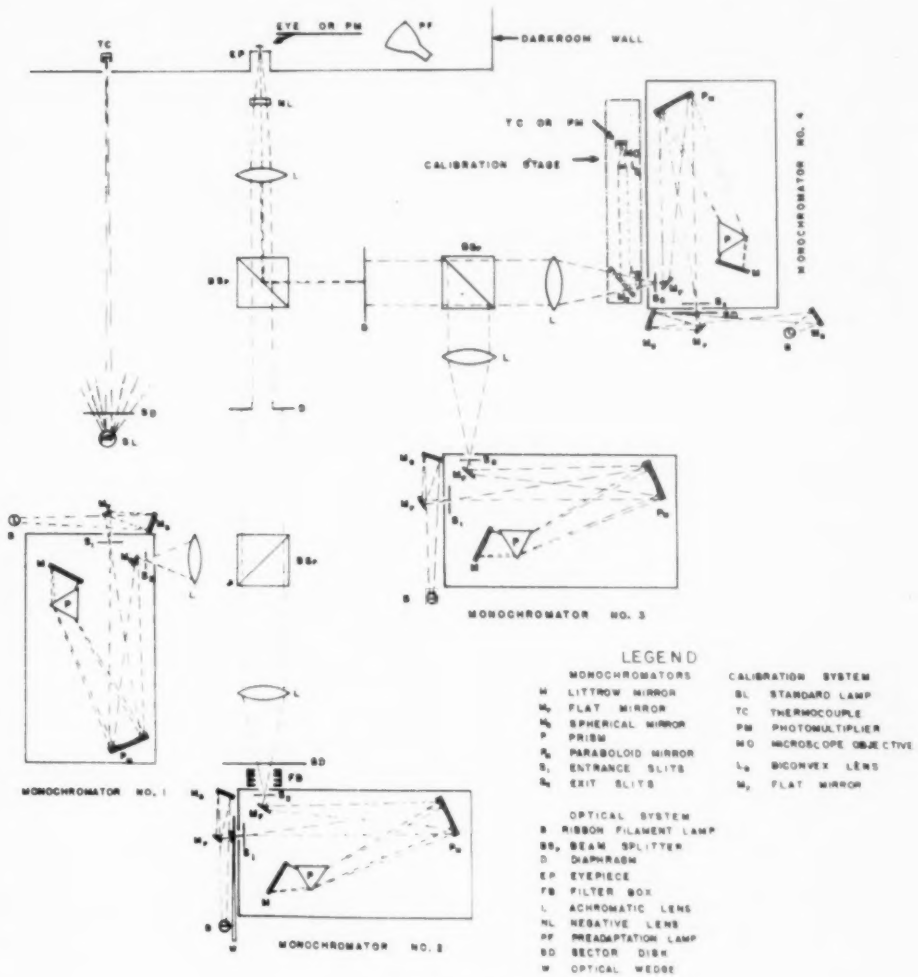

FIG. 2. The Fordham colorimeter.

as a light source. The diverging light from the filament was collected and reflected by a spherical mirror onto a flat mirror which deflected the rays of light through an intensity control system, to be described later, and located a real image of the filament on the entrance slits of the monochromator. These slits were controlled by a micrometer, calibrated in millimeters. Slit widths could be reproduced to .001 of a millimeter. The light passing through the slits became a diverging beam which was collected and collimated by a paraboloid mirror. The light reflected from this mirror then passed through the prism, fell on the Littrow mirror and was reflected back through the prism to the paraboloid. The return path of the light was at a slightly different angle from the original pathway. The paraboloid reflected the light, now in a converging beam, onto a small flat mirror which reflected it onto the exit slits. A real image of the source was focused on the exit slits. From the exit slits, the light diverged until it passed through an achromatic lens, 1.875 in. in diameter with a focal length of 11 in. This lens was positioned at its focal length from the exit slits and collimated the beam of light.

The dispersion characteristics of the monochromator are 5 mμ per millimeter of slit width at 400 mμ and 30 mμ at 700 mμ. To guard against stray light, various Kodak Wratten or Corning colored glass filters were used across the beams at the exit slits.

Optical System

In the description of the monochromators given above, an arrangement was described whereby each of the monochromators delivered a collimated beam of light to the optical system. These four beams of light were combined by means of beam splitters. Each of these was made from two glass right angle prisms. On the hypotenuse surface, a half silver reflecting coat had been applied. The prisms were cemented together, yielding a cube whose dimensions were 3 in. per side. Two of the three beam splitters were used each to combine the light of two monochromators and the third beam splitter was used to combine these double beams. The four light beams were then transmitted to another double convex lens which converged the beam of light and directed it onto a negative lens which formed an image of the light source at the artificial pupil. The combination of the double convex lens and the negative lens yielded a focal length of 15 in.

In this optical system, there were two places at which diaphragms could be inserted to determine the size of a beam of light which fell upon the eye. There was an optical pupil for each of the monochromators between the light source and the spherical mirror. This position was used whenever it was necessary to diaphragm each of the four beams separately. Where it was permissible to diaphragm two beams simultaneously, the focal points marked on Fig. 2 were employed.

Accessory Equipment

Power supply. The power for the light sources was delivered by a Sorenson Nobatron, Model E-6-40A. This instrument received power from the ordinary 110 AC house mains. It transformed this current down to six or seven volts, depending on the operation, and converted, by means of selenium rectifiers, the alternating current to direct current. An electronic voltage control apparatus regulated the current and kept it constant within the limits of one tenth of one per cent. A 6-v. storage battery was connected across the Nobatron output in order to eliminate any current ripples not removed by the voltage control regulator.

Control of light intensity. Intensity of the light was controlled on three of the monochromators by means of Kodak neutral tint photographic wedges with balancers. These wedges have a range of slightly more than four logarithmic units. They were positioned directly in front of the entrance slits to the monochromators. Each one had been calibrated for transmission factors at the Electrical Testing Laboratories in New York City and in the laboratories here, using a Farrand photomultiplier photometer. Whenever the wedges have been calibrated in the laboratory, they have been in position in the colorimeter and the photomultiplier tube has been located at the eyepiece. The logarithm of the transmission was determined for whatever wavelengths were used in the experimentation. The fourth monochromator employed an extra set of slits for intensity control. Light from the bulb was focused on these slits by means of a short focal-length, spherical mirror and the path of the light from this point on was the same as in the other monochromators. This arrangement was introduced into the colorimeter in order to make provision for certain types of research which need high intensity values of light.

Timing mechanisms. This piece of apparatus consisted of a sector disc driven by a Bodine Constant Speed Motor and a solenoid operated shutter. The sector disc rotated at a rate of 50 rpm. The solenoid operated shutter was placed at the entrance slits of Monochromator 2. A push button for its operation was located at the *S*'s chair in the dark room. In this circuit were located two microswitches which were operated by a cam fixed to the shaft on which the sector disc was mounted. Their operation was such that an electrical impulse to the solenoid for the opening of the shutter could occur only when the sector disc was in a definite position. This arrangement removed the possibility of the shutter opening after the sector disc had begun to cross the diaphragm through which the stimulus light passed. In this way a stimulus light of the same duration was always insured. The duration of the stimulus flash was a function of the size of the sector cut from the disc. Different stimulus durations were obtained by using different

sector discs. In the present experiment, the stimulus duration was varied from one part to another and will be stated where appropriate.

Monitoring. In order to ascertain the constancy of the power applied to the light source, a voltmeter was connected across the storage battery, and an ammeter was connected in series with the light source. These were checked regularly throughout the testing sessions. As a further intensity control, a Weston photronic cell was placed in close proximity to whichever one of the four light sources required critical observation. The cell was connected in series with a microammeter. The deflections of this latter instrument were watched for any indication of shifts in the energy emitted by the light source during the progress of the research.

Calibration: Equipment and Procedures

Wavelength

Wavelength calibration was carried out by using a 100-w. AH4 General Electric mercury arc and Geissler tubes filled with neon, hydrogen, argon, and helium. The arc or a Geissler tube was substituted for the light source in the monochromator which was to be calibrated. The wavelength drum was then turned until one of the identifiable spectral lines was focused in the eyepiece and the drum setting was recorded. The drum was then moved until another line was picked up. A group of some 15 lines spread across the spectrum was located. A graph was then plotted of wavelength versus drum settings. This plot yielded a smooth curve. Other spectral locations were then obtained from the graph.

Intensity

A Farrand photomultiplier photometer was used for purposes of intensity calibration. The photometer head was furnished with one of three phototubes depending upon the type of calibration required. The phototubes were R.C.A. 1P21, 1P22, and 6217. All tubes were calibrated for relative spectral sensitivity for each wavelength employed during this research. For the greater part of the time radiometric measurements in arbitrary units were sufficient. The units employed were the scale units of the galvanometer of the photometer corrected to give equal response regardless of wavelength.

After the laboratory acquired the thermocouple with its amplifier and indicating equipment (a Ballantine voltmeter), the units in which the apparatus was calibrated were microwatts from which calculations could be made to the number of quanta involved. The method whereby this was accomplished was to calibrate the thermocouple against a carbon filament standard lamp. This lamp was calibrated by the Electrical Testing Company for flux output in terms of microwatts per centimeter square. The lamp was calibrated at four different amperage values. A plot of voltage readings from the Ballantine versus the calibration values of the standard lamp yielded a straight line which passed through the calibration points and the origin. The slope of this line was the conversion factor whereby the voltage readings of the Ballantine were converted into microwatts.

While, ideally speaking, it would have been desirable to place the thermocouple at the eyepiece and make readings directly from the Ballantine, there was not enough light at the shorter wavelengths to permit this. Consequently, an indirect method was employed. A special bracket was designed which, by means of lenses and an inverted microscopic objective, focused the output of Monochromator 4 on the thermocouple. This was so mounted that it could be precisely manipulated in each of the three main axes. With this mounting it was possible to locate the thermocouple so that it received all the light from the monochromator. The monochromator was calibrated for whatever combination of wavelength and pass band was desired. After this the thermocouple was removed and the phototube placed so that its center received the light which formerly fell on the thermocouple. The scale unit deflections of the phototube galvanometer were obtained and a ratio of microwatts per scale unit deflection was calculated. When the phototube was employed to calibrate the colorimeter, it was placed at the artificial pupil at the point where the *S* located his eye.

Procedure

This research treats of seven related topics. Part 1 deals with the photopic luminosity curves of the four *S*s who carried out the major portion of this experimentation. This is included to demonstrate that these *S*s had essentially normal color vision. Part 2 reports the data obtained from the investigation of the problem of photosensitization, i.e., the differential threshold for foveal vision at low background levels. Part 3 was a preliminary investigation into the variability of the standard deviation with wavelength. The findings obtained here led directly to Part 4 which consists in an extensive study of the same problem. Parts 5 and 6 were logical developments of Part 4. Part 5 studied the variation of the standard deviation under fixed conditions of *S*, field size, and method, at a few specified wavelengths. This yielded an estimate of the minimum variability of the standard deviation over a period of time. Part 6 treats of the same problem with the added parameter of field size, introducing the possibility of greater variability. The last part presents quantum estimates of the mean values of the data from the preceding part. Because the precise experimental conditions varied considerably from one part to another, the part procedures will be described each in its own section of the results.

Subjects

Nine *S*s took part in this investigation; eight males and one female. The age ranged from the middle forties for one *S*, the middle thirties for another, to the mid-twenties for the remaining *S*s.

Results

Part 1: Photopic Luminosity Curves of Four Ss

The photopic luminosity curves of the four *S*s whose data will form the substance of Parts 2, 3, and 4 of this monograph are presented here. The field used was a circular disc subtending one degree of visual angle. It flashed into the center of the fovea for durations of one-twentieth of a second. The data for *S*s I and II are taken directly from the work of Dillon (1954) because of the identity of the *S*s. Each value given for these two *S*s represents the average of 50 determinations. The ascending method of limits was employed. Five threshold determinations were made at each of 31 wavelengths per session, and there were 10 sessions. The order of presentation of the wavelengths was varied systematically from session to session. The curves of *S*s III and IV were derived from frequency-of-seeing curves. One frequency-of-seeing curve was obtained for each wavelength. Each curve was based upon 50 determinations made at each of five energy levels. The points were plotted on probit paper with the logarithm of the energy as the abcissa and percentage of seeing as the ordinate. The data fell on straight lines and the fit was made by eye. The 50% seeing point was taken as the mean value. It had been planned to report luminosity data derived from the data of Part 4 of the work, but noise developing in the phototube made some of the mean values suspect and it was decided not to include them in this paper.

At the time when the curves were obtained, the laboratory had not been equipped with the thermocouple and its auxiliary apparatus. The units of energy used were the scale deflections of the photometer galvanometer corrected for the differential sensitivity of the 1P22 phototube. After the new equipment had been put into working condition, *S*s I and II made extensive judgments at wavelength 550 mμ and the microwatt values for these data were obtained. It is worthy of note that the wedge settings were within .02 log units of those obtained during the original data gathering. The differences among the wedge settings of the four *S*s at 550 mμ were calculated and, by means of these differences, the microwatt

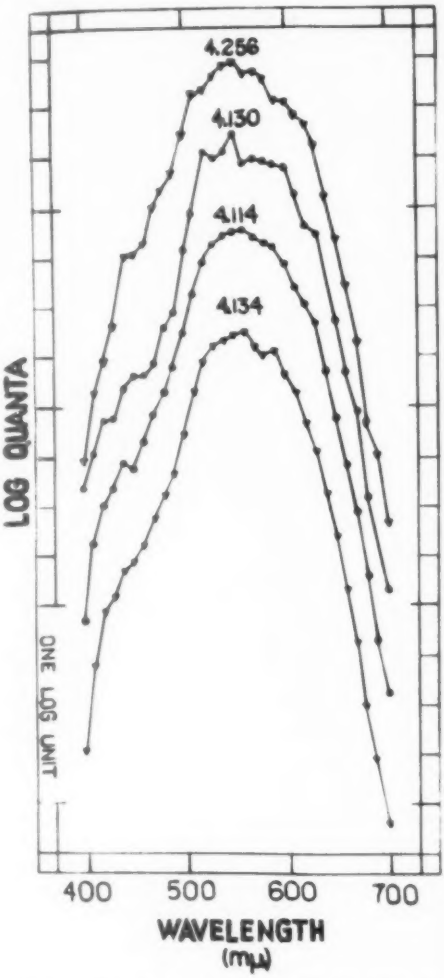

Fig. 3. Foveal luminosity curves for four *S*s. Number indicates log quanta values for each *S* at λ = 550 mμ.

values for *S*s III and IV were obtained. The 550 mμ values were then used to calculate the microwatt values for the four *S*s at all wavelengths. The microwatt values were then converted into ergs and divided by the proper quantal value ($h\nu$) for each wavelength.

The data of the luminosity curves for the four *S*s are given in Table 1 and Fig. 3. The number at the maximum of each curve is the log quanta threshold energy value for wavelength 550 mμ. The ordinate scale is in .10 log units. The curves of all four *S*s depart from the smoothness of the I.C.I. curve. However, in units of microwatts they have been compared with those recently published by Hsia and Graham (1952), and Hurvich and Jameson (1953), and so closely agree with them that any discrepancies are felt to be accounted for in terms of individual differences. All show inflections varying in amount between 440 and 450 mμ, and again at 490 mμ. These inflections have been interpreted by Wald (1948) to represent absorption of light energy by macular pigment at these wavelengths. Others have claimed that the same irregularities are due to the activity of the different color receptor systems within the eye. Except for these small inflections of the curves there is apparently no other significant deviation from the smooth curve. All of the *S*s show the maximum at 550 mμ, excepting *S* I who shows it at 560 mμ.

Comparing the threshold values between the point of maximum sensitivity and 400 mμ, we find the following: *S* I exhibits the greatest range, approximately 2.26 log units;

TABLE 1

LOGARITHM OF THE NUMBER OF QUANTA REQUIRED FOR THRESHOLD FOVEAL LUMINOSITY CURVES FOR FOUR *S*s

Wavelength (mμ)	*S* I	*S* II	*S* III	*S* IV
400	6.228	6.061	5.9435	6.2693
410	5.801	5.692	5.7212	5.9307
420	5.512	5.486	5.5603	5.7812
430	5.450	5.405	5.5134	5.5733
440	5.322	5.281	5.3996	5.2317
450	5.274	5.301	5.3413	5.2378
460	5.196	5.161	5.3432	5.1961
470	5.049	5.017	5.2965	4.9848
480	4.918	4.908	5.0982	4.8860
490	4.829	4.798	5.0307	4.8155
500	4.617	4.625	4.6923	4.6428
510	4.408	4.420	4.5106	4.4449
520	4.287	4.262	4.2125	4.3997
530	4.199	4.179	4.2473	4.3405
540	4.161	4.130	4.2210	4.2902
550	4.134	4.114	4.1300	4.2560
560	4.111	4.114	4.2819	4.3385
570	4.207	4.146	4.2512	4.3266
580	4.223	4.161	4.2594	4.3524
590	4.212	4.196	4.2791	4.4693
600	4.342	4.272	4.3128	4.4581
610	4.418	4.401	4.4323	4.5384
620	4.581	4.476	4.5804	4.5940
630	4.716	4.573	4.6181	4.6883
640	4.928	4.812	4.8198	4.9433
650	5.146	5.053	5.0688	5.1506
660	5.420	5.290	5.3205	5.3875
670	5.697	5.526	5.5178	5.6700
680	6.004	5.848	5.9567	6.0592
690	6.265	6.164	—	6.2389
700	6.576	6.441	6.4211	6.5755

S II, a range of 2.08; *S* IV, a range of 1.91; and *S* III, a range of 1.72. These ranges are considerably less than those which were set up by the I.C.I. photopic luminosity curve and their range corresponds approximately to the respective ages of the *S*s.

Part 2: The Differential Threshold in Foveal Vision, i.e., Photosensitization

The hypothesis of photosensitization, as previously mentioned, states that whenever a signal light is made to appear against graded series of background intensities ranging from zero value to values well above the cone threshold, the energy required by the flash of light in order to be seen one-half of the time is minimal, not at zero background, as would be expected, but at some low background value. In other words, the presence of a dim surround of monochromatic light should lower the threshold value of a signal light seen against the background.

For this part of the experiment, four monochromatic bands of light, 5 mμ in width, centered at 480 mμ, 509 mμ, 550 mμ, and 670 mμ, respectively, were employed. These four wavelengths were used in the 16 possible combinations as background and signal. For the background, a range of 9–12 intensity levels was used. In all cases, the lowest level was that of zero intensity. The second intensity level was approximately at rod threshold for the dark adapted eye and the following levels were arranged in steps, each of which was half a logarithmic unit above that of the preceding step. In this way, the range of background from none at all, through rod threshold, up to and beyond cone threshold was investigated. The highest background in all cases represented the maximal amount of light which the apparatus was capable of delivering under the prescribed conditions of wavelength and pass band. The method of determining the threshold value for the signal light was that of constant stimuli. Five points within the range of the *S*'s doubtful responses were roughly determined. At each of these five determined points, the *S* was given, in completely random fashion, 50 stimulations to which he reported seeing or not seeing the flash of light. Hence, each frequency-of-seeing curve is based upon 250 responses. For ease in manipulating the apparatus, each of these five points was separated by approximately .20 to .25 of a logarithmic unit. The frequency-of-seeing curves were plotted on probit paper, the abcissa being the logarithm of the intensity and the ordinate the percentage of response. The curves describing the data were all straight lines and from these lines the mean and standard deviations were taken. The mean value was calculated from the 50% point and the standard deviation from

$$\frac{\text{Log } E_{(.8413)} - \text{Log } E_{(.1586)}}{2}$$

Two *S*s were employed in this part of the experiment. The signal light was fixated in the fovea by means of a tiny red fixation point. In the early stages of the experimentation, the signal light subtended a visual angle of 1.5°. After the experiment was in progress, the field of the signal light was reduced to one degree of visual angle, to better insure the fact of purely foveal stimulation. The signal light was centered in the background which subtended a visual angle of approximately 9.5°.

The basic data for this part of the experiment are contained in Table 2 and Fig. 4. In each of these experimental situations, the first step in the procedure was to obtain a mean and a standard deviation from a frequency-of-seeing curve for the signal light under conditions of zero background. The 1.5° field was used by *S* I for the four wavelengths of the signal light against the 480 mμ background light. *S* II also used it for the 480 mμ signal light against the 480 mμ background. At this point, the field size was reduced to one degree. This change has the effect of slightly raising the threshold. Beyond this, the change of the field has no real effect upon the experiment. Each signal light was tested four times with a zero background in the case of each *S*. Due to the change in field size, *S* I obtained only three absolute threshold values under

TABLE 2

MEAN AND STANDARD DEVIATION IN ARBITRARY UNITS OF THE LOGARITHM OF THE ENERGY FOR TWO *Ss* AND FOUR TEST LIGHTS AGAINST FOUR BACKGROUNDS AT VARIOUS LEVELS OF BACKGROUND ILLUMINATION

S	Logarithm of Background Intensity in Arbitrary Units	Background Light							
		480 mμ		509 mμ		550 mμ		670 mμ	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
		Signal Light 480 mμ							
I	0.0	−0.397	0.133	−0.438	0.180	−0.350	0.167	−0.155	0.120
	1.0	—	—	−0.505	0.135	−0.467	0.120	—	—
	1.5	—	—	−0.445	0.166	−0.467	0.151	—	—
	2.0	—	—	−0.474	0.130	−0.467	0.144	—	—
	2.5	−0.387	0.165	−0.421	0.132	−0.503	0.144	−0.288	0.120
	3.0	−0.328	0.127	−0.433	0.144	−0.432	0.132	−0.216	0.131
	3.5	−0.343	0.192	−0.447	0.151	−0.432	0.132	−0.337	0.153
	4.0	−0.466	0.148	−0.457	0.147	−0.479	0.120	−0.385	0.142
	4.5	−0.237	0.102	−0.450	0.109	−0.360	0.108	−0.385	0.110
	5.0	−0.304	0.108	−0.428	0.120	−0.384	0.120	−0.288	0.142
	5.5	−0.286	0.199	−0.306	0.139	−0.168	0.132	−0.404	0.153
	6.0	−0.122	0.204	−0.101	0.170	−0.071	0.108	−0.312	0.164
	6.5	—	—	—	—	—	—	−0.288	0.164
	7.0	—	—	—	—	—	—	−0.312	0.175
	7.5	—	—	—	—	—	—	−0.070	0.153
II	0.0	−0.229	0.144	*−0.148*	0.133	*−0.238*	0.138	*−0.251*	0.169
	1.0	—	—	−0.162	0.157	−0.045	0.145	—	—
	1.5	−0.157	0.149	−0.167	0.169	−0.115	0.120	—	—
	2.0	−0.169	0.127	−0.109	0.133	−0.197	0.138	—	—
	2.5	−0.229	0.163	−0.131	0.133	−0.228	0.160	—	—
	3.0	−0.152	0.142	−0.119	0.145	−0.223	0.172	—	—
	3.5	−0.229	0.135	−0.131	0.145	−0.146	0.124	−0.276	0.125
	4.0	−0.272	0.168	−0.114	0.121	−0.243	0.182	−0.148	0.120
	4.5	−0.296	0.125	−0.041	0.145	−0.211	0.165	−0.208	0.145
	5.0	−0.217	0.204	−0.072	0.085	−0.024	0.148	−0.280	0.142
	5.5	−0.253	0.168	0.161	0.109	0.123	0.160	−0.220	0.145
	6.0	−0.161	0.113	0.353	0.121	0.281	0.165	−0.078	0.169
	6.5	—	—	—	—	—	—	−0.022	0.120
	7.0	—	—	—	—	—	—	−0.122	0.108
	7.5	—	—	—	—	—	—	0.351	0.140
		Signal Light 509 mμ							
I	0.0	*−1.103*	0.136	*−0.739*	0.168	*−0.841*	0.132	*−0.818*	0.110
	1.0	—	—	−0.836	0.127	−0.903	0.125	—	—
	1.5	−1.177	0.143	−0.808	0.115	−0.846	0.137	—	—
	2.0	−1.179	0.134	−0.801	0.138	−0.834	0.125	—	—
	2.5	−1.200	0.138	−0.854	0.155	−0.868	0.148	—	—
	3.0	−1.211	0.132	−0.824	0.142	−0.784	0.137	—	—
	3.5	−1.234	0.205	−0.815	0.152	−0.823	0.114	−0.894	0.110
	4.0	−1.234	0.151	−0.780	0.157	−0.823	0.114	−0.927	0.099
	4.5	−1.204	0.109	−0.819	0.150	−0.789	0.125	−0.807	0.176
	5.0	−1.149	0.131	−0.808	0.150	−0.743	0.137	−0.796	0.154
	5.5	−1.149	0.161	−0.635	0.170	−0.573	0.148	−0.840	0.110
	6.0	−1.025	0.151	−0.301	0.108	−0.288	0.125	−0.905	0.143
	6.5	—	—	—	—	—	—	−0.840	0.165
	7.0	—	—	—	—	—	—	−0.686	0.143
	7.5	—	—	—	—	—	—	−0.466	0.176

TABLE 2 (continued)

	0.0	*−0.754*	0.184	*−0.631*	0.117	*−0.701*	0.135	*−0.628*	0.115
	1.0	—	—	−0.631	0.117	−0.605	0.104	—	—
	1.5	−0.773	0.156	−0.596	0.140	−0.763	0.140	—	—
	2.0	−0.800	0.161	−0.608	0.128	−0.616	0.124	—	—
	2.5	−0.796	0.128	−0.631	0.163	−0.644	0.145	—	—
	3.0	−0.800	0.150	−0.608	0.117	−0.568	0.101	—	—
	3.5	−0.796	0.161	−0.596	0.082	−0.586	0.115	−0.559	0.131
II	4.0	−0.823	0.115	−0.585	0.186	−0.547	0.143	−0.531	0.127
	4.5	−0.800	0.150	−0.608	0.163	−0.556	0.094	−0.711	0.152
	5.0	−0.773	0.138	−0.596	0.105	−0.352	0.159	−0.692	0.127
	5.5	−0.573	0.131	−0.491	0.117	−0.094	0.131	−0.605	0.115
	6.0	−0.356	0.104	−0.352	0.093	—	—	−0.547	0.110
	6.5	—	—	—	—	—	—	−0.508	0.150
	7.0	—	—	—	—	—	—	−0.301	0.110
	7.5	—	—	—	—	—	—	−0.174	0.115

Signal Light 550 mμ

	0.0	*−1.309*	0.113	*−1.149*	0.165	*−1.050*	0.132	*−1.106*	0.173
	1.0	—	—	−1.275	0.132	−1.006	0.165	—	—
	1.5	−1.287	0.171	−1.149	0.198	−1.149	0.143	—	—
	2.0	−1.236	0.160	−1.127	0.176	−1.105	0.187	—	—
	2.5	−1.331	0.170	−1.149	0.132	−1.050	0.132	—	—
	3.0	−1.251	0.182	−1.204	0.143	−1.050	0.143	—	—
	3.5	−1.214	0.186	−1.138	0.121	−1.050	0.143	−1.041	0.152
I	4.0	−1.203	0.190	−1.193	0.154	−0.973	0.153	−1.073	0.206
	4.5	−1.300	0.164	−1.171	0.132	−0.973	0.132	−1.062	0.130
	5.0	−1.236	0.195	−1.105	0.154	−0.973	0.132	−1.041	0.065
	5.5	−1.192	0.173	−0.951	0.132	−0.929	0.132	−1.149	0.173
	6.0	−1.103	0.244	−0.545	0.121	−0.622	0.153	−1.041	0.087
	6.5	—	—	—	—	—	—	−1.030	0.130
	7.0	—	—	—	—	—	—	−0.813	0.173
	7.5	—	—	—	—	—	—	−0.629	0.108
	0.0	*−1.220*	0.115	*−0.995*	0.112	*−1.224*	0.100	*−0.957*	0.113
	1.0	—	—	−0.966	0.101	−1.190	0.245	—	—
	1.5	−1.225	0.200	−0.977	0.123	−1.246	0.134	—	—
	2.0	−1.203	0.175	−0.981	0.146	−1.135	0.134	—	—
	2.5	−1.125	0.177	−0.954	0.184	−1.202	0.134	—	—
	3.0	−1.092	0.140	−0.894	0.218	−1.079	0.111	—	—
	3.5	−1.103	0.155	−0.977	0.166	−1.035	0.111	−0.954	0.144
II	4.0	−1.072	0.160	−0.966	0.123	−0.957	0.145	−0.957	0.113
	4.5	−1.082	0.188	−0.954	0.146	−0.968	0.189	−0.932	0.133
	5.0	−0.963	0.153	−0.965	0.146	−0.957	0.156	−0.972	0.122
	5.5	−0.977	0.164	−0.802	0.135	−0.812	0.156	−0.855	0.127
	6.0	−0.852	0.111	−0.707	0.164	−0.456	0.111	−0.855	0.138
	6.5	—	—	—	—	—	—	−0.695	0.138
	7.0	—	—	—	—	—	—	−0.484	0.173
	7.5	—	—	—	—	—	—	−0.262	0.093

Signal Light 670 mμ

	0.0	*−0.673*	0.113	*0.300*	0.114	*0.378*	0.153	*0.244*	0.099
	1.0	—	—	0.379	0.148	0.378	0.194	—	—
	1.5	—	—	0.368	0.148	0.344	0.166	—	—
	2.0	—	—	0.368	0.148	0.355	0.180	—	—
	2.5	−0.717	0.120	0.436	0.136	0.469	0.166	—	—
	3.0	−0.789	0.156	0.391	0.136	0.469	0.153	—	—
	3.5	−0.831	0.184	0.266	0.136	0.378	0.166	0.189	0.155
I	4.0	−0.774	0.134	0.334	0.148	0.469	0.153	0.322	0.110
	4.5	−0.750	0.114	0.300	0.159	0.458	0.125	0.322	0.141
	5.0	−0.768	0.103	0.368	0.125	0.424	0.139	0.288	0.099
	5.5	−0.731	0.127	0.459	0.136	0.537	0.166	0.260	0.128
	6.0	−0.623	0.175	0.641	0.114	0.674	0.208	0.344	0.152
	6.5	—	—	—	—	—	—	0.443	0.139
	7.0	—	—	—	—	—	—	0.553	0.143
	7.5	—	—	—	—	—	—	0.939	0.137

TABLE 2 (continued)

	0.0	*0.300*	0.107	*0.503*	0.139	*0.235*	0.134	*0.322*	0.112
	1.0	—	—	0.449	0.137	0.226	0.116	—	—
	1.5	0.275	0.093	0.449	0.086	0.190	0.108	—	—
	2.0	0.318	0.114	0.469	0.148	0.204	0.094	—	—
	2.5	0.300	0.091	0.424	0.109	0.231	0.101	—	—
	3.0	0.350	0.102	0.478	0.107	0.276	0.090	—	—
	3.5	0.352	0.095	0.401	0.137	0.287	0.103	0.275	0.114
II	4.0	0.363	0.095	0.446	0.137	0.249	0.112	0.237	0.085
	4.5	0.350	0.109	0.394	0.123	0.349	0.067	0.260	0.123
	5.0	0.316	0.114	0.471	0.125	0.334	0.105	0.237	0.157
	5.5	0.504	0.118	0.435	0.196	0.506	0.090	0.271	0.134
	6.0	0.686	0.068	0.585	0.141	0.614	0.112	0.376	0.103
	6.5	—	—	—	—	—	—	0.580	0.143
	7.0	—	—	—	—	—	—	0.562	0.123
	7.5	—	—	—	—	—	—	0.712	0.157

the conditions of a one degree field. *S* II obtained four absolute threshold values for each signal light for all of the wavelengths except the 480 mμ signal light against the 480 mμ background. These absolute values, when compared with each other, serve as an index of the consistency of the *S*s throughout the period of this experimentation. The mean and standard deviations obtained under these conditions of zero background have been printed in italics in Table 2 for ease of comparison.

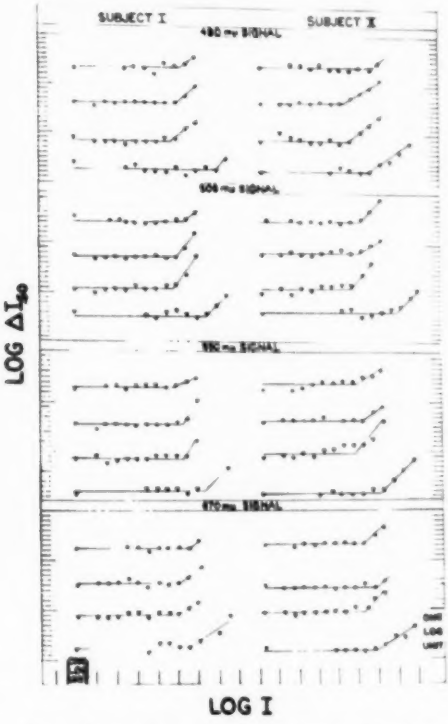

FIG. 4. Log ΔI_{∞} values for various log I_0 values. Background: Open circles −480 mμ, closed circles −509 mμ, open triangles −550 mμ, closed triangles −670 mμ.

As shown by these figures, the shift in mean absolute threshold values throughout a time interval of 24 months is less than three-tenths of a logarithmic unit. In five of the eight cases it is less than .15 of a logarithmic unit. Denton and Pirenne (1954) accept as permissible a shift in mean absolute threshold values of .20 of a logarithmic unit, under conditions of maximum stability. Hecht (1944) presents data showing a variability of .30 of a logarithmic unit in absolute threshold determinations. It is clear that the variability of the *S*s of this experiment lies within established limits.

An examination of the data contained in Table 2, background by background, and *S* by *S*, shows that for all background and signal light combinations (except for the three highest background intensities under all these conditions), the shift in mean values of the intensity of the signal is less than .29 of a logarithmic unit. Out of the 32 possible combinations of *S*, signal and background lights, we find a range of mean values of signal light intensity of less than .15 log units in 18 situations, of less than .20 in nine others, of less than .25 in four others, and in only one case does

the value exceed .25. In only one combination of signal and background lights (480 mμ, signal; 670 mμ, background) do both *S*s show a range of over .20 log units in mean variability of the signal light at the lower levels of background intensity. In all 32 situations, the two or three highest background intensities show a mean value of the signal light whose magnitude is definitely increasing. This region of background intensities is interpreted as that background level at which the value of the differential threshold begins to increase. If the data pertaining to the three highest levels of background intensity are not considered for the moment, the following ranges of mean scores have been obtained. In approximately three-fourths of the *S*, test-light, background combinations, the range of mean scores is less than .20 of a logarithmic unit. The remaining cases, where the range is more than this value, show the variability of one *S* to be large while that of the other is small. There is only a single case where both *S*s show a range of mean variability of more than .20 of a logarithmic unit. In this isolated case there is no regular pattern in the variation of the mean. It is difficult to conclude to a process of photosensitization when the mean variability at different background intensities is not larger than that of the variability of the absolute threshold.

Weber's law has been shown not to hold throughout the range of intensities to which the eye is capable of responding (Hecht, 1934). The commonly accepted opinion is that the absolute value of $\triangle I$ increases with an increase in I. The evidence of the present research is that under conditions where the $\triangle I$ flash is completely confined to the fovea its value is that of the absolute threshold for all levels of the background intensity which are below the cone threshold itself.

The simplest explanation for the constancy of $\triangle I$ through this range is that the rate of breakdown of photochemical substances is so slow and the amount so small that the restoration process is easily able to counterbalance it and to leave the cones in a state in which they possess a concentration of photochemical substances which is very close to 100%. The rise in $\triangle I$ at those levels of background illumination which are above the cone threshold would then be explained by the fact that the rate of restoration is not able to bring the concentration of photochemical substances back to a level closely approximating the maximum.

A study of the standard deviations given in Table 2 shows that they vary in an unpredictable fashion from session to session within a wavelength over a range of .03 to .145 log units. It is felt that because of the irregularities manifested in the standard deviations, they represent, purely and simply, day-to-day variability. If the size of the standard deviation were being determined by variations in the wavelength of either the signal or the background, or their intensity, or both, one would expect that both the range of the standard deviation and the average value of the standard deviations would yield a pattern. The pattern, if it exists, is not evident in the data. The average size of the standard deviation of the logarithm of the energy appears to be determined by factors other than the intensity of the wavelength of either background or signal light.

Part 3: Preliminary Investigation of Variability of the Standard Deviation

The failure of the research just reported to yield evidence of photosensitization led to further work to determine whether photosensitization was very definitely an individual phenomenon. It is a priori possible that individual differences in the makeup of retinal elements might be sufficient to bring about photosensitization with different combinations of signal and background for different people. One might indirectly answer this latter question by discovering whether the pattern of variation of the standard deviation of the logarithm of threshold energy was or was not subject to a wide range of individual variation. Consequently, two *S*s were set the task of obtaining frequency-of-seeing curves at wavelengths throughout the visual spectrum from 410 to 700 mμ. The wavelengths

tested were separated by intervals of 10 mμ and the pass band was 5 mμ. At each of these points, each of the two *S*s obtained a frequency-of-seeing curve according to the same method as was employed in Part 2, namely, five points were chosen within the range of doubtful response and the *S* was tested with 50 determinations at each of these five points. As previously, the intensity of the stimuli was varied in a random fashion. The signal light subtended a visual angle of one degree of arc. The fixation point was a single red dot centered on the field where the signal light would flash. The results of this experiment are given in Table 3 and Fig. 5. The curves of Fig. 5 lend superficial support to the concept that the maxima and minima of the standard deviations obtained from frequency-of-seeing curves are different for different *S*s. Once these data had been obtained, the question arose regarding their reliability. This then led to the development and the planning of Part 4 of the experiment.

TABLE 3

STANDARD DEVIATIONS OF THE LOGARITHM OF THRESHOLD ENERGY VALUES (*SD* LOG. E_{50}) IN ARBITRARY UNITS FOR TWO *S*s AND 30 WAVELENGTHS (5mμ PASS BAND) OBTAINED FROM FREQUENCY-OF-SEEING CURVES

Wavelength (mμ)	*S* III	*S* IV
410	.139	.136
420	.113	.133
430	.122	.143
440	.122	.127
450	.100	.104
460	.118	.107
470	.132	.106
480	.109	.122
490	.111	.097
500	.121	.077
510	.126	.092
520	.106	.099
530	.118	.128
540	.142	.132
550	.113	.126
560	.151	.113
570	.135	.091
580	.128	.088
590	.128	.123
600	.130	.103
610	.130	.105
620	.122	.123
630	.180	.136
640	.125	.094
650	.123	.090
660	.149	.105
670	.120	.100
680	.134	.120
690	.205	.109
700	.140	.099

Part 4: Extensive Investigation of the Variability of the Standard Deviation of the Logarithm of Threshold Energy

In this phase of the investigation 36 wavelengths were studied. These were spaced at 10 mμ intervals from 410 to 700 mμ with the addition of 435, 445, 475, 485, 505, and 575 mμ. The stimulus light subtended 30 min. of arc. Two *S*s were employed. Two basic psychophysical methods were used; the method of constant stimuli and the method of limits. The method of constant stimuli was employed in the same fashion as in the preceding sections except that 50 blank stimuli were randomly interspersed with the 250 regular stimuli. The number of positive responses to blanks was used as an index of the attention and care with which the *S*s made their observations. The method of limits was employed in the following manner.

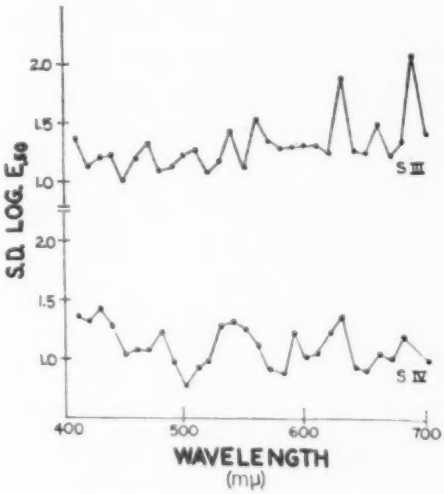

FIG. 5. Standard deviation (*SD* Log E_{50}) values for two *S*s (method of constant stimuli).

Only the ascending phase of the method was used because it was desirable to avoid any possibility of changing the *S*'s state of dark adaptation. The method was used first on a straightforward threshold basis; then it was used on a basis of flicker response to a one-to-one light–dark ratio flash repeated at the rate of 20 flashes per second. For each type of threshold and for each wavelength, 25 determinations were made by each *S*. They were made, however, in five separate sessions, with five determinations at each of the wavelengths at each session. In order to control fatigue effects, the same rotational design employed by Dillon (1954) was used. In the first session, the *S* began with the 410 mμ wavelength and continued to the longer wavelengths until the 36 wavelengths had been tested. In the second session, the *S* began with wavelength 460 mμ and continued to 700 mμ, and then was tested from 410 to 450 mμ. In the third session, the *S* began at 520 mμ, and continued in the same fashion as in the preceding sessions. The fourth session began at wavelength 580 mμ, and the fifth at wavelength 640 mμ.

In order to secure greater accuracy of fixation, use was made of the phenomenon of chromatic parallax. Monochromator 4 was set to deliver a monochromatic beam of red light and Monochromator 3, a monochromatic beam of green light. These two beams were combined by Beam Splitter 2. In their path, at the focal point lying between Beam Splitters 2 and 3, a diaphragm with a circular opening subtending 1–2 min. of arc was inserted. The red and green beams of monochromatic light both passed through this opening and were directed by the remainder of the optical system to the center of the artificial pupil, and there brought to a focus. Due to the aberration produced by the eye, there is a tendency for the shorter wavelengths to come to a focus at the retina in front of the longer wavelengths. As a result, there is one and only one position on the retina where the two tiny spots coincide to give a single yellow dot. At all other positions two tiny spots appear—one red and the other green. In setting up the signal light, the *S* viewed the fixation point and adjusted his head and the chin rest until he was able to see a single yellow fixation point. The *S* then directed the experimenter who adjusted the position of the signal light field so that the fixation point fell in its center.

The results of this work, employing the method of constant stimuli, are contained in Tables 4 and 5, and in Fig. 6. An analysis of variance was undertaken with regard to the data obtained with the method of constant stimuli from both *S*s for 36 wavelengths and three sessions at each wavelength. The statistical model which fits this type of data is described by McNemar (1955) as Case VII, i.e., a mixed model wherein the rows stand for the different *S*s; the columns for the wavelengths; and there is measurement replication leading to three scores per cell. In this model the variance estimate of individual differences is used as the error term to test the significance of the interaction. The interaction variance is used to test the main effects of *S* and wavelength. The results of this analysis are given in Table 6. In this case, the interaction variance estimate as tested against the variance estimate of individual differences is not significant at the .05 level of confidence. Hence, the individual responses do not differ by more than can be expected on the basis of errors of measurement. Using the interaction estimate as the error term, it is found that the *S*s are significantly different one from the other. This is an expected result whenever measurements attain a reasonable degree of pre-

TABLE 4

NUMBER OF AFFIRMATIVE RESPONSES TO "BLANK" STIMULI

(TOTAL NUMBER OF CURVES—108 PER *S*)

S	Curves with Affirmative Responses			
	0	1	2	3
I	59	30	11	8
III	42	38	21	7

TABLE 5

STANDARD DEVIATIONS OF THE LOGARITHM OF THRESHOLD ENERGY VALUES (*SD* LOG E_{th}) IN ARBITRARY UNITS FOR TWO *Ss* AND 36 WAVELENGTHS (5 mμ PASS BAND) OBTAINED FROM FREQUENCY-OF-SEEING CURVES

Wavelengths	*S* I				*S* III				Average Two *Ss*
	Session			Average	Session			Average	
	1	2	3		1	2	3		
410	.194	.169	.154	.172	.166	.112	.122	.133	.1525
420	.182	.187	.183	.184	.181	.138	.114	.144	.164
430	.183	.187	.154	.175	.128	.145	.121	.131	.153
435	.174	.179	.155	.169	.157	.119	.143	.140	.1545
440	.182	.221	.179	.194	.137	.165	.113	.138	.166
445	.197	.179	.168	.181	.124	.131	.118	.124	.1525
450	.177	.123	.138	.146	.093	.145	.148	.129	.1375
460	.165	.164	.158	.162	.158	.114	.125	.132	.147
470	.156	.213	.143	.171	.110	.119	.114	.114	.1425
475	.127	.153	.118	.133	.146	.133	.118	.132	.1325
480	.148	.173	.160	.160	.171	.119	.130	.140	.150
485	.149	.132	.183	.155	.149	.134	.095	.126	.1405
490	.152	.190	.140	.161	.114	.125	.103	.114	.1375
500	.201	.114	.134	.150	.187	.115	.110	.137	.1435
505	.134	.142	.143	.140	.124	.128	.128	.125	.1335
510	.165	.125	.172	.154	.143	.132	.081	.119	.1365
520	.177	.122	.184	.161	.156	.117	.097	.123	.142
530	.186	.206	.179	.190	.119	.128	.119	.122	.1485
540	.161	.139	.119	.140	.107	.110	.099	.105	.1225
550	.187	.175	.115	.159	.082	.108	.086	.092	.1255
560	.149	.136	.154	.146	.167	.158	.098	.141	.1435
570	.199	.180	.171	.183	.160	.121	.130	.137	.160
575	.195	.145	.144	.161	.108	.120	.135	.121	.141
580	.156	.187	.145	.163	.133	.120	.166	.140	.1515
590	.211	.166	.146	.174	.131	.138	.146	.138	.156
600	.146	.192	.089	.142	.125	.147	.108	.127	.1345
610	.139	.148	.157	.148	.077	.103	.133	.104	.126
620	.155	.132	.155	.147	.110	.130	.139	.126	.1365
630	.155	.173	.136	.155	.079	.127	.140	.115	.135
640	.175	.217	.140	.177	.130	.155	.188	.158	.1675
650	.163	.136	.123	.141	.105	.134	.138	.126	.1335
660	.193	.121	.128	.147	.123	.142	.159	.142	.1445
670	.149	.212	.155	.172	.126	.095	.140	.120	.146
680	.145	.145	.166	.152	.129	.138	.134	.134	.143
690	.209	.186	.158	.184	.119	.101	.151	.124	.154
700	.136	.149	.127	.137	.116	.092	.120	.109	.123

cision. The *F* ratio of wavelength versus interaction yielded a value which just attained significance at the .05 level. In tracking down the causes of this significant ratio, two further analyses were carried out —one on each *S*. *S* III showed no significant differences. *S* I showed differences due to wavelength which were significant at the .01 level. The question of the more exact location of the differences was solved by means of Tukey's test for significance. Once wavelengths 420, 440, 445, 530, 570, and 690 mμ were removed from the matrix, the analysis failed to yield an *F* ratio significant at the .05 level. Study of the individual *SD* Log E scores for the above-mentioned wavelengths shows that there is in five of the six cases one large value

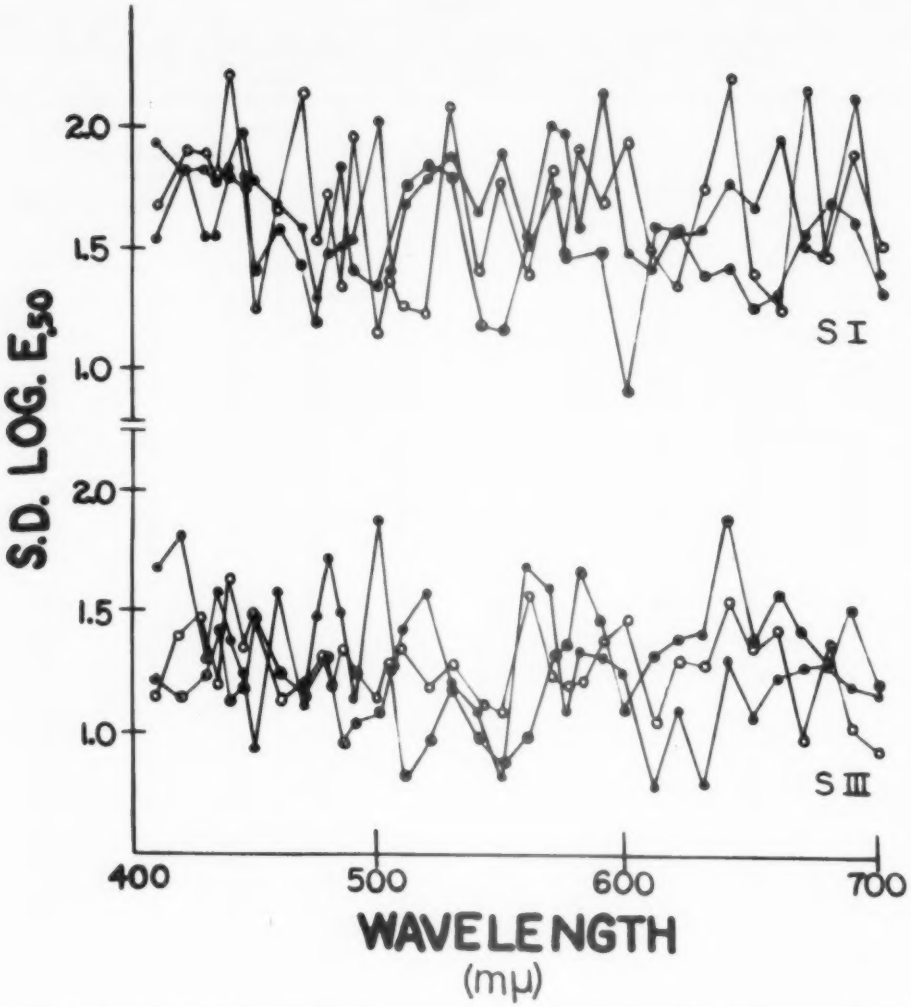

FIG. 6. Standard deviation (*SD* Log E_{50}) values for two *S*s with three determinations per *S* per λ (method of constant stimuli).

together with two values of average magnitude. It is the large value which is producing the significant *F* ratio. There is nothing consistent in the values for the three sessions. In only one case, wavelength 420 mμ, is there consistency in large values for the three sessions. However, this trend is not borne out by *S* III. Intercorrelations between the scores for the three sets of data per *S* yield coefficients of .099, .097, .183 for one *S*, and .136, .067, .166 for the other. With this lack of consistency between the sets of measures it is concluded that no evidence is offered for a quasi-periodic variation of the *SD* Log E values with wavelength, as yielded by the method of constant stimuli.

After the work upon the magnitude of

TABLE 6

AN ANALYSIS OF VARIANCE OF THE STANDARD DEVIATION OF THE LOGARITHM OF THRESHOLD ENERGY VALUES ACCORDING TO THE VARIABLES OF *Ss* AND WAVELENGTHS WITH THREE REPLICATIONS

Source	*SS*	*df*	Variance Estimate	*F*
Ss	60,200	4	60,200	127.00
Wavelength	29,279	35	836	1.76
Interaction	16,507	35	474	1.16
Individual difference	58,554	144	407	
Total	164,621	215		

the standard deviation, obtained by the method of constant stimuli, was completed, attention was given to determining the pattern of variation in the standard deviation when the ascending method of limits was used. As detailed in the procedure, each *S* gave five threshold determinations at each of 36 wavelengths during a session, and there were five such sessions, totaling 25 determinations per wavelength per *S*. Because interest centered on the magnitude of the standard deviation and any effect of day-to-day variability, contributed by the mean to this value, should be excluded, the standard deviation was obtained from the data in the following manner. The magnitude of the deviates was determined by subtracting the values of each five determinations from the average of the same five determinations. The 25 deviations thus obtained were squared and summed and divided by *N* and the square root extracted. It was felt that this would yield what might be called a refined measure of variability and one which would be uncontaminated by whatever causes produce the small but definite day-to-day variability in mean values reported in the literature. This would also give greater comparability to the standard deviations obtained by the method of constant stimuli where each standard deviation is determined as the variability around the mean value of the session from which it is taken. With this method of calculation, one finds that the variability is extremely small. The standard deviations obtained from the data, computed this way, are as small or smaller than those normally reported in the literature. In no case does a single standard deviation reach a value of .10 of a logarithmic unit. The data are given in Table 7 and Fig. 7.

In addition to using the strict threshold method, standard deviations were again obtained, using the ascending series of the

TABLE 7

STANDARD DEVIATIONS OF THE LOGARITHM OF THRESHOLD ENERGY VALUES (*SD* LOG E) IN ARBITRARY UNITS FOR TWO *Ss* AS DETERMINED BY THE ASCENDING METHOD OF LIMITS FOR ABSOLUTE THRESHOLD AND CRITICAL FUSION FREQUENCY THRESHOLDS

	S I		*S* III	
Wavelength (mμ)	Threshold	C.F.F.	Threshold	C.F.F.
410	.064	——	.033	——
420	.049	——	.048	.030
430	.073	.045	.050	.026
435	.056	.051	.054	.043
440	.032	.052	.030	.048
445	.049	.036	.034	.053
450	.049	.052	.052	.036
460	.061	.062	.042	.052
470	.073	.041	.031	.052
475	.048	.063	.046	.040
480	.051	.052	.043	.046
485	.063	.064	.040	.047
490	.060	.034	.047	.046
500	.061	.056	.036	.050
505	.041	.040	.058	.051
510	.041	.038	.035	.040
520	.042	.050	.046	.046
530	.058	.042	.044	.030
540	.062	.062	.031	.047
550	.044	.071	.017	.044
560	.053	.048	.041	.033
570	.063	.059	.038	.055
575	.064	.043	.024	.051
580	.044	.067	.051	.056
590	.057	.045	.045	.046
600	.059	.051	.051	.052
610	.033	.073	.036	.050
620	.084	.049	.034	.039
630	.080	.055	.071	.085
640	.063	.084	.051	.049
650	.061	.054	.049	.089
660	.067	.041	.039	.082
670	.056	.047	.031	.041
680	.054	.052	.038	.044
690	.055	.050	.048	.029
700	.080	——	.049	——

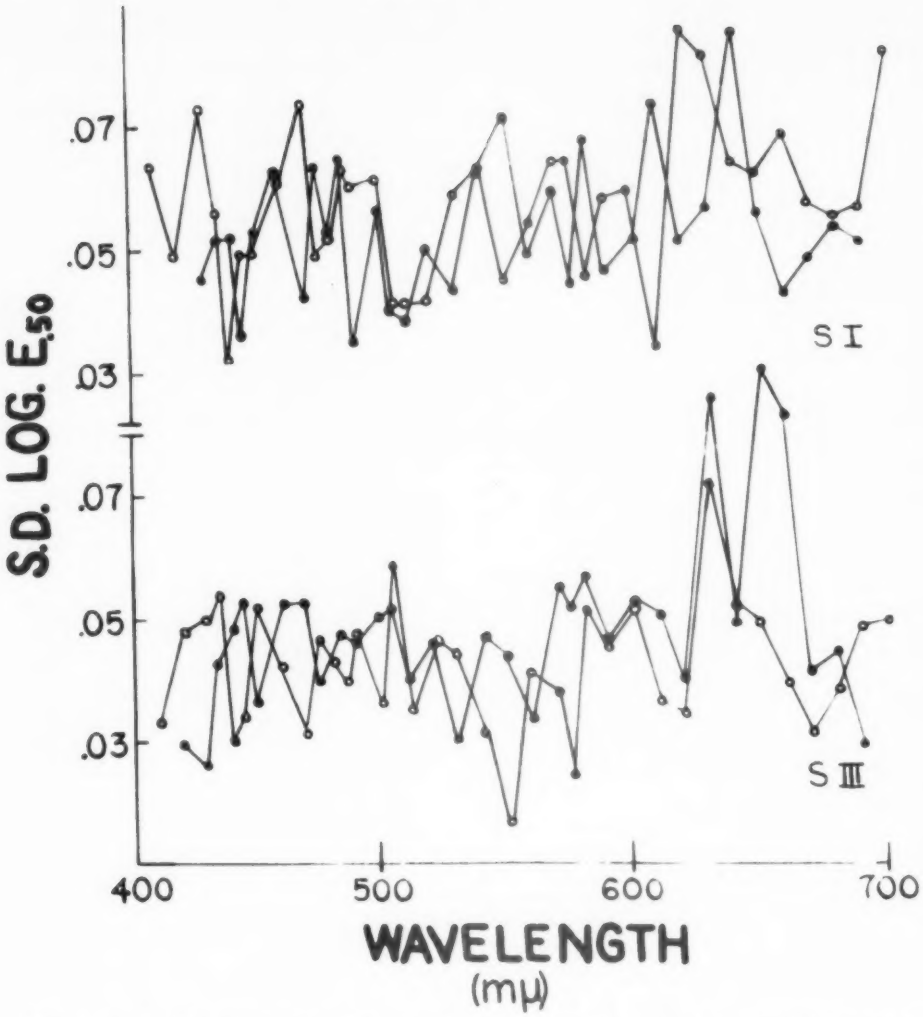

FIG. 7. Standard deviation (*SD* Log E_{ω}) values for two *S*s. Open circles, threshold; closed circles, C.F.F.

method of limits for obtaining the point of critical fusion frequency. This critical fusion frequency was obtained for a flash rate of 20 flashes of light per second, with a light–dark ratio of 1.0. This flash rate is sufficiently high to insure that the critical fusion frequency threshold will be at the cone level. The lack of determinations at wavelengths 410 mμ and 420 mμ for *S* I, and 410 mμ for *S* III, were due to the fact that the monochromator did not give sufficient light in the violet region of the spectrum for critical fusion frequency determination at this relatively high rate of flash frequency. These data are also given in Table 7. The standard deviations were calculated in exactly the same way as they were for the threshold data obtained by the method of limits. The magnitude of the standard deviations is approximately the

TABLE 8

PRODUCT-MOMENT CORRELATIONS
(Constants, Flicker and Threshold)

S	Method	C.F.F.	Threshold
I	Constants	−0.09	−0.21
	C.F.F.		−0.13
II	Constants	−0.03	0.31
	C.F.F.		0.19

same and in the same range as in the case of the threshold data. When these data had been gathered, Pearson product-moment correlation coefficients were then calculated for the data of each of the *S*s and each of the three methods of obtaining the standard deviations. These data are presented in Table 8. None of the correlation coefficients is significant; two of them are only insignificantly different from zero correlations, two are very small insignificant negative correlations, and two are low positive correlations. It is very difficult to conceive that there is an important function of wavelength producing a significant periodic variability throughout the spectrum when correlations of this completely nonsignificant magnitude are obtained.

Part 5: Determination of Variability at Specified Wavelengths

The failure to obtain any confirmation of the periodic variability of the standard deviation of the logarithm of the threshold values led immediately to the question of whether, within a wavelength, variability of .20 of a logarithmic unit was excessive and must be attributed to some factor other than session-to-session variability. Hence, Part 5 of this research was designed.

The apparatus and general procedure was the same as for the constant stimuli section of Part 4 with the exception of two minor changes in the apparatus. The fixation point was changed from a tiny dot in the center of the signal light to one which consisted of two very small dots placed one on each side of the signal light. This was done in order to remove the possibility that the fixation point might in any way influence the results. The size of the signal light field was reduced from .50° to .26° because the periodic variability was thought to be enhanced by smaller fields. Four *S*s, who had not been involved in any of the previous work, were given the task of gathering data extensively on a group of eight wavelengths. Wavelengths 435, 460, 506, 545, 575, 609, 622, 670 mμ were chosen. The *S*s were divided into two groups, each of which was responsible for the data of four of the selected wavelengths, two of which were in spectral locations where large standard deviations were predicted by Crozier and two where small values were expected. At each of these wavelengths 10 frequency-of-seeing curves for each of the *S*s were obtained using the method of constant stimuli in exactly the same manner as described in the previous section. Standard deviations were calculated from these curves. This large number of standard deviations was obtained in order to discover whether or not the postulated periodic variation of the standard deviation with wavelength was a real phenomenon, but one so small in magnitude that it would escape detection if determined by as small a number as three standard deviations per wavelength. The data for this portion of the research are contained in Table 9.

An examination of the data shows that there is no obvious pattern. There is no evident tendency for decrease of standard deviation with practice. *S* VI yields at the fifth session, the largest values in three of the four wavelengths for which he was subject. *S* VII yields his largest values at the last session, second session, first session, and the sixth session. *S* VIII has his largest values once in the last session, and the other three in the first two sessions. It is also to be noted that the values of the standard deviations are of approximately the same magnitude as those obtained by *S*s I, II, III, and IV. The size of the standard deviation ranges from .085 to .263 log units, with less than 10% of the total number attaining values of .20 or larger. It seems difficult to draw any conclusions

TABLE 9

STANDARD DEVIATION OF THE LOGARITHM OF THRESHOLD ENERGY VALUES FOR EIGHT WAVELENGTHS, FOUR *S*s, AND 10 SESSIONS PER WAVELENGTH

Session	Wavelengths							
	435 mμ	460 mμ	506 mμ	545 mμ	575 mμ	609 mμ	622 mμ	670 mμ
	S V				*S* VII			
1	.201	.137	.174	.135	.125	.120	.255	.112
2	.162	.163	.181	.118	.104	.221	.155	.130
3	.173	.182	.135	.156	.170	.125	.150	.133
4	.234	.215	.189	.138	.146	.152	.164	.116
5	.120	.214	.177	.149	.119	.168	.161	.107
6	.165	.167	.137	.133	.133	.150	.117	.157
7	.234	.183	.118	.150	.124	.131	.165	.090
8	.204	.249	.224	.128	.115	.125	.121	.112
9	.240	.217	.181	.162	.137	.123	.111	.110
10	.263	.183	.181	.1781	.177	.119	.158	.100
Mean *SD*	.200	.191	.170	.145	.135	.143	.156	.117
Range	.143	.112	.089	.060	.073	.102	.144	.067
Session	*S* VI				*S* VIII			
1	.168	.128	.099	.114	.163	.221	.161	.122
2	.132	.109	.127	.139	.135	.220	.152	.164
3	.110	.085	.109	.117	.096	.170	.097	.141
4	.132	.116	.156	.106	.135	.126	.142	.170
5	.164	.223	.180	.156	.129	.146	.137	.144
6	.165	.131	.123	.114	.160	.115	.111	.103
7	.160	.148	.169	.087	.127	.142	.087	.122
8	.137	.161	.104	.113	.159	.132	.124	.139
9	.136	.160	.123	.096	.132	.110	.133	.107
10	.159	.197	.135	.112	.169	.160	.141	.137
Mean *SD*	.146	.146	.133	.115	.141	.154	.129	.135
Range	.055	.138	.081	.069	.073	.111	.055	.067

from these data beyond the fact that the variability from session to session is of approximately the same order for all four *S*s. It is felt that this phase of the experiment represents a fairly good sample of *S* variability in the task of obtaining frequency-of-seeing curves under constant conditions of wavelength, field size, field position, and time of exposure.

An inspection of the data shows that the range of 10 standard deviations within one wavelength and for one *S* is less than .150 log units at the maximum and .055 at the minimum, with other values assuming intermediate positions. The important conclusion to be drawn from these data is that a group of standard deviations obtained during a series of sessions yields values whose ranges amount to between 25% and 50% of the values assigned by Crozier (1950) as representing a real shift in the standard deviation as a function of wavelength. The pattern of the average standard deviations (averaging all standard deviations for both *S*s and for each wavelength) shows a trend of a steady decrease from the violet end of the spectrum to the red. It is suggested that this decrease should be interpreted in line with the generally established fact that variability from session to session and from *S* to *S* is greater in the shorter wavelengths than in the longer. It would seem, then, that the standard deviation reflects directly the magnitude of the

TABLE 10

AVERAGE VALUES (FROM 15 FREQUENCY-OF-SEEING CURVES) OF THE STANDARD DEVIATION OF THE ENERGY AT FOUR WAVELENGTHS AND THREE FIELD SIZES, AND FOR TWO *Ss*[a]

Field Size	*S*	Wavelengths			
		460 mμ	506 mμ	546 mμ	575 mμ
3 min.	I	.172 (.0238)	.168 (.0175)	.128 (.0208)	.143 (.0225)
	II	.216 (.0340)	.168 (.0169)	.161 (.0209)	.161 (.0175)
30 min.	I	.158 (.0137)	.165 (.0193)	.155 (.0211)	.156 (.0168)
	II	.170 (.0223)	.178 (.0179)	.146 (.0249)	.163 (.0168)
45 min.	I	.160 (.0250)	.136 (.0150)	.141 (.0171)	.159 (.0132)
	II	.150 (.0194)	.121 (.0154)	.126 (.0166)	.130 (.0208)

[a] Entries in parentheses represent the *SDs* of the *SDs* taken as raw scores (arbitrary Log E units).

variability of the mean values. If this interpretation is correct, Crozier's (1950) contention that visual threshold values are best described in terms of a logarithmic Gaussian distribution is not borne out. One of the reasons presented by him, as decisively proving that a Poisson distribution could not describe visual threshold data, was that the standard deviation varied periodically with wavelength, and that its magnitude was completely independent of the magnitude of the mean value. The data obtained from this research in no way support this contention. Hence, whether a Poisson distribution, an arithmetical Gaussian distribution, or a logarithmic Gaussian distribution represents the best mathematical model for the purpose of describing threshold data obtained by the method of constant stimuli, is still a problem requiring determination. This same conclusion has been reached by Blackwell (1953).

Part 6: Further Determination of the Variability of the Standard Deviation With Changing Field Size

The last aspect of the study of the variation of the standard deviation involved its magnitude as a function of field size. Four 5-mμ bands of monochromatic light were again used. These bands were centered on 460, 506, 546, and 575 mμ and were chosen because two of them represented spectral bands where maximal values and two where minimal values of the standard deviation were to be found according to the data of Crozier (1950). Because there was evidence that field size might have an effect on the function, three field sizes were used which subtended, at the cornea, visual angles of 3, 30, and 45 min. of arc. The method of constant stimuli was used in exactly the same manner as in Parts 4 and 5 to obtain frequency-of-seeing curves. Two *Ss* each obtained 15 of these curves for each combination of wavelength and field size.

The mean and standard deviation for each frequency-of-seeing curve was calculated by means of the Muller-Urban system of weights. Table 10 gives the average values of the standard deviations obtained in this experiment. Each entry represents the average of 15 standard deviations. The measure is the standard deviation of the logarithm of the energy expressed in arbitrary units.

A three-way analysis of variance employing these average values as entries was calculated. The main effects studied were wavelength, field size, and *Ss*. Table 11 gives the pertinent data yielded by the analysis. This experimental plan comes under McNemar's classification of a mixed model, and is similar to his Case XIV (McNemar, 1955). Following this guide, the triple interaction value was used to test

TABLE 11

ANALYSIS OF VARIANCE FOR THE AVERAGE STANDARD DEVIATION VALUES FROM FOUR WAVELENGTHS, THREE FIELD SIZES, AND TWO *Ss*

Source	*SS*	*df*	Variance Estimate
Wavelength	2,518	3	839
Field Size	2,847	2	1,424
Ss	81	1	81
Wavelength × Field Size	1,598	6	266
Wavelength × *Ss*	291	3	97
Field Size × *Ss*	1,650	2	825
Wavelength × Field Size × *Ss*	531	6	89

the two-way interactions; the wavelength-*S* interaction was used to test the effect of wavelength, and the field size-*S* interaction was used to test the effects of field size. The *F* ratios show significance at the .05 level for field size-*S* interaction. All other interactions are insignificant at this level of confidence. Among the main effects, neither field size nor wavelength effects are significant at the .05 level. This conclusion is in line with the findings of previous research in this laboratory, but directly at variance from the data of Crozier (1950). The data reported here are those of two *S*s. In previous sections the work relative to this same matter was described. This involved six *S*s over and above the present two. All the results are in agreement. Since Crozier's data were obtained from a single *S*, it would seem that the weight of evidence at the moment is against the proposition that the magnitude of the standard deviation is influenced by wavelength.

Part 7: Quantal Estimates of Mean Values Obtained at Four Wavelengths

The frequency-of-seeing curves described in the preceding section supplied a large amount of data the mean values of which had been calculated in radiometric units, namely, microwatts. It was entirely a matter of calculation to change these units into quanta. The formula used was:

$$\frac{\text{Energy in Ergs}}{h\nu}$$

where h is Planck's constant and ν is the frequency of the light. The values were also corrected for the duration of the flash which was .02 sec. The estimates are, therefore, of the total number of quanta delivered in the flash. They are given in Table 12 and represent that number of quanta at the cornea at which the stimulus is seen 50% of the time. With these data as a base, further calculations were carried out in order to discover the number of quanta which actually entered into the photoreceptors and produced the threshold sensation.

Because aberration is a necessary concomitant of light flashes delivered through optical systems with small apertures, correction for this was the first step in an evaluation of the quanta-receptor ratio. Five different approaches to the problem offered themselves. The first one was derived from a statement made by Nolan (1957) that Karn's (1936) data on the relationship of time and intensity show that aberration increased the size of his fields by 7.3–7.4 min. of arc. Though the fields in this experiment were smaller than the two larger ones employed here, calculations were carried out using a correction factor of 7 min. of arc. The retinal field diameters were then assumed to subtend angles of 10, 37, 52 min. of arc. Using these retinal areas together with the cone density ratios calculated from Polyak's (1941) data, the ratios of quanta per cone were derived.

In addition to the calculations carried out according to the theories of Nolan (1957), two further analyses were done, each according to two slightly differing assumptions. If a piece of frosted glass is placed at the artificial pupil of the apparatus, the light pattern appearing in the pupil has the form of a vertical bar of light across the center of the artificial pupil. The height of the light bar is determined by the diameter of the artificial pupil which is 2.5 mm. The width of the bar is a function of (*a*) the width of the exit slit of the monochromator, and (*b*) the magnification of the optical system. This latter is determined by the focal length of the lenses in the beam of light. The collimating lens in the front of the monochromator has a focal length of

TABLE 12

ESTIMATED NUMBER OF QUANTA FOR THRESHOLD (50% POINT ON FREQUENCY-OF-SEEING CURVES) FOR FOUR WAVELENGTHS, THREE FIELD SIZES, AND TWO *S*s

Field Size	*S*	Wavelength			
		460 mμ	506 mμ	546 mμ	575 mμ
3 min.	I	8,484	1,945	994	1,306
	II	12,078	2,598	1,266	1,261
30 min.	I	75,935	23,449	9,807	12,741
	II	84,396	25,882	13,235	17,221
45 min.	I	154,260	32,290	15,851	15,846
	II	180,240	54,324	35,845	35,844

11 in. The converging lens and the negative lens, located in proximity to the artificial pupil, yield, in combination, a focal length of 15 in. Hence, the magnification factor of the system is 1.36364.

The first formula to be applied to the data is the same as that used by Wright (1947).

$$\theta = \frac{2.44 \times \lambda \times 10^{-3}}{NP'}$$

where θ is the angular subtense to the first ring of the Airy diffraction disc, λ is the wavelength in microns, N is the refractive index of the vitreous humor—equal to 1.34, P' is the width or the length, respectively, of the light patch at the artificial pupil. Width equals slit width × 1.34354. Length equals the diameter of the artificial pupil, i.e., 2.5 mm.

A second method of determining the size of the angle is the use of the ratio

$$\text{sine } \theta = \frac{\lambda}{w}$$

where λ is the wavelength in microns and w is the width or length of the light patch at the artificial pupil.

Judging from the fact that what the *S* sees is reported as a circle of light, the diffraction pattern on the retina must be some sort of an ellipse whose distortion is so small that it is not appreciated by the *S* as being really different from a circle. Certainly the greatest possible amount of distortion would be that of a rectangular patch of light. In order to cover all possibilities, both of the formulae just mentioned were used to calculate the height and the width of the patch of light. Then these two dimensions were used to complete the area of a rectangle and an ellipse according to the standard formulae. Again Polyak's (1941) data was employed to derive quanta-per-cone ratios.

The next factor to be considered in this process of determining the effective number of quanta at the receptor level is that of the absorption of light both by the ocular media and, since these data are foveal, by the macular pigment. The quantum-per-cone ratios were corrected using the transmission factors of Ludwig and McCarthy and of Wald as tabulated by Judd (1951).

The final correction which had to be made was for the effective absorption of the quanta by the photochemical substance within the cones. It is not known exactly what this factor is, but it is commonly held that it is less than the absorption factor of visual purple, which is probably in the neighborhood of 10% (Pirenne & Denton, 1952).

The results of these calculations as applied to each method of correction for diffraction are contained in Table 13. The two columns headed No. 1 contain the quanta-per-cone ratios without any corrections made for diffraction. Columns No. 2 and No. 3 give the quanta-per-cone ratios using the formula from Wright; columns No. 2, rectangle; columns No. 3, ellipse. Columns No. 4 and No. 5 give the results when employing the sine formula with columns No. 4, rectangle, and columns No. 5, ellipse. Columns No. 6 give the results using Nolan's (1957) suggested correction. These data show ratios of from 51 to 6 quanta per 100 cones. The higher ratios are concentrated especially at wavelengths of 460 and 506 mμ and the 3-min. field. This pattern is consistent with the decreased sensitivity at the foveal center for the shorter wavelengths in the visual spectrum. The differences between the ratios for these two wavelengths with the 3-min. field and the 45-min. field are of the same order found by Sperling and Hsia (1957) and by Wright (1947).

Polyak (1941) speaks of two types of cone systems in the foveal area. Anatomically these systems are for the most part identical in their component structures. However, they are undoubtedly different in their functioning. They are called, respectively, the common, or multisynaptic, system and the private, or monosynaptic, system. The midget bipolar (h) and the midget ganglion cell (s) are essential to the functioning of the monosynaptic system. The common system can function without their involvement. Since it is well known that visual acuity is proportional to the intensity of the stimulating light, most probably the monosynaptic system is the mecha-

TABLE 13

QUANTA PER CONE RATIO WITHOUT CORRECTIONS FOR ABERRATION AND WITH CORRECTION FOR SAME (CORRECTION FOR PHOTO PIGMENT ABSORPTION INCLUDED)

Field Size	Wavelength	S I							S II						
		1	2	3	4	5	6	Av.	1	2	3	4	5	6	Av.
3 min.	460	1.4	.27	.35	.28	.36	.10	.27	2.0	.39	.50	.40	.51	.14	.39
	506	1.2	.20	.25	.16	.20	.09	.18	1.6	.26	.33	.21	.27	.14	.24
	546	1.0	.12	.16	.10	.12	.08	.12	1.5	.16	.21	.12	.16	.09	.15
	575	1.3	.14	.18	.12	.16	.10	.14	1.3	.14	.17	.12	.15	.10	.14
30 min.	460	.2	.12	.15	.11	.14	.11	.13	.2	.13	.17	.12	.15	.12	.14
	506	.2	.14	.18	.12	.15	.13	.14	.2	.15	.18	.12	.15	.13	.15
	546	.1	.09	.11	.07	.09	.08	.09	.2	.12	.15	.10	.12	.12	.12
	575	.2	.10	.13	.10	.13	.12	.12	.2	.14	.18	.13	.17	.16	.16
45 min.	460	.2	.12	.15	.10	.13	.11	.12	.2	.14	.17	.12	.15	.13	.14
	506	.2	.09	.11	.08	.10	.09	.09	.3	.15	.19	.13	.17	.15	.16
	546	.1	.07	.09	.06	.07	.07	.07	.3	.15	.19	.13	.17	.16	.16
	575	.1	.06	.08	.06	.08	.08	.07	.3	.15	.19	.14	.18	.17	.15

Note.—See text for explanation of numbers at head of columns.

nism whereby high visual acuity is mediated. It would not be stretching an hypothesis too far to assume that the (h) bipolar and the (s) ganglion cell mediate impulses at light intensities corresponding to a high index of visual acuity. Since the mop bipolar (d) is apparently not involved in foveal or cone vision, only the (e) and (f) [(g) is probably a freak form of either (e) or (f)] are functioning in foveal threshold vision.

Excluding the short wavelengths and the smallest field, a flux density of one quantum per 6–14 cones is required for threshold responses at the central portion of the luminosity curve. The (e) and (f) bipolars are related to the cones in a ratio of one bipolar for every 6–12 cones. This brings up the interesting hypothesis that the flux density in quanta is related to the diffuse types of foveal bipolars in approximately a one-to-one ratio.

SUMMARY

The results of this investigation show:

1. There is no evidence for the process of photosensitization insofar as the four chosen wavelengths are concerned.

2. There is no evidence for the variation, as a function of wavelength, in the magnitude of the standard deviation of the logarithm of threshold energy as indicated by: (*a*) an investigation at 36 wavelengths by three psychophysical methods, (*b*) an extensive investigation of eight wavelengths by the method of constant stimuli, (*c*) an extensive investigation of four wavelengths with three different field sizes.

3. The magnitude of $\triangle I$ in relation to the background is of exactly the same value as the absolute threshold for that particular wavelength, until the background has attained an intensity which is higher than the cone threshold.

4. In conformity with the statements of Denton and Pirenne (1954), it must be assumed that day-to-day variability over a long period of time is of a magnitude of approximately .20 of a logarithmic unit.

5. The estimated number of quanta required for foveal stimulation after appropriate corrections have been made lies between 10–50 quanta per hundred cones at the 3-min. field, between 18 to 7 per hundred cones at the 30-min. field, and between 19 to 6 per hundred cones at the 45-min. field.

REFERENCES

BLACKWELL, H. R. Studies of the form of visual threshold data. *J. Opt. Soc. Amer.*, 1953, **43**, 456-463.

CROZIER, W. J. On the visibility of radiation at the human fovea. *J. gen. Physiol.*, 1950, **34**, 87-136.

DENTON, E. J., & PIRENNE, M. H. The absolute sensitivity and functional stability of the human eye. *J. Physiol.*, 1954, **123**, 417-441.

DILLON, D. J. An investigation of threshold variability in the determination of the photopic luminosity curve. Unpublished manuscript, Fordham Univer. Library, 1954.

HECHT, S. Vision II: The nature of the photoreceptor process. In Murcheson (Ed.), *A handbook of general experimental psychology*. Worcester, Mass.: Clark Univer. Press, 1934. Pp. 704-828.

HECHT, S. Energy and vision. *Amer. Scientist*, 1944, **32**, 159-177.

HSIA, Y., & GRAHAM, C. H. Spectral sensitivity of the cones in the dark adapted human eye. *Proc. Nat. Acad. Sci.*, 1952, **38**(1), 80-85.

HURVICH, L. M., & JAMESON, DOROTHEA. Spectral sensitivity of the fovea: I. Neutral adaptation. *J. Opt. Soc. Amer.*, 1953, **43**, 485-494.

JUDD, D. B. Basic correlates of the visual stimulus. In S. S. Stevens (Ed.), *Handbook of experimental psychology*. New York: Wiley, 1951. Pp. 811-867.

KARN, H. W. Area and the intensity-time relation in the fovea. *J. gen. Psychol.*, 1936, **14**, 360-369.

MCNEMAR, Q. *Psychological statistics*. New York: Wiley, 1955.

NOLAN, G. F. On the functional relation between luminous energy, target size, and duration for foveal stimuli. *J. Opt. Soc. Amer.*, 1957, **47**, 394-397.

PIRENNE, M. H., & DENTON, E. J. Accuracy and sensitivity of the human eye. *Nature*, 1952, **170**, 1039.

POLYAK, S. L. *The retina*. Chicago: Univer. of Chicago Press, 1941.

SPERLING, H. G., & HSIA, H. Some comparisons among spectral sensitivity data obtained in different retinal locations with two sizes of foveal stimulus. *J. Opt. Soc. Amer.*, 1957, **47**, 707-713.

WALD, G. Photochemistry of vision. In F. P. Fischer, A. J. Schaeffer, & A. Sorsby (Eds), *Documenta opthalmolgica*, Vol. 3. 'S-Gravehage, Hollandia: Dr. W. Junk, 1948. Pp. 94-137.

WRIGHT, D. W. *Researches on normal and defective color vision*. St. Louis: Mosby, 1947.

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